Ice radiance method for BUV instrument monitoring

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ABSTRACT

The radiance of large, ice covered land masses has been used to monitor TOMS instrument sensitivities. Greenland and Antarctica provide uniform and stable ice surfaces whose average albedo appears to be constant within the desired accuracy for instrument monitoring. Instrument radiance response will depend upon view and illumination angles, the sun-earth distance, and atmospheric conditions. Restriction to nadir views eliminates view angle dependence, and corrections are made for sun-earth distance. The effect of atmospheric conditions, such as ozone and clouds, is minimized by monitoring at wavelengths above 340 nm and by the high surface radiance. Relative instrument response is determined by the ratio of signals measured at different times using a binning technique to account for differences in solar illumination angles. The only remaining limit to long term monitoring accuracy is the albedo stability of the ice surface itself. Changes in the Nimbus-7/TOMS instrument response at long wavelengths are monitored within 1% accuracy over the lifetime of the instrument.

2. INTRODUCTION

A series of instruments utilizing the Backscatter Ultraviolet (BUV) technique[1] for measuring atmospheric ozone have been launched beginning in 1970. These instruments include 2 Total Ozone Mapping Spectrometers (TOMS) and 5 Solar Backscatter Ultraviolet (SBUV) spectrometers. Each instrument contains onboard calibration systems to track instrument radiance sensitivity. These calibration systems have become steadily more sophisticated and precise as the difficulties associated with maintaining instrument calibration have become better understood. The discovery of significant decreases in global ozone and the ozone hole over Antarctica further emphasized the need for accurate instrument calibration over long time periods. In particular, the nearly 15 year data record from the TOMS instrument onboard the Nimbus-7 (N7) spacecraft has been the primary means of measuring ozone trends.

The N7/TOMS calibration system[2], which consists of a single ground aluminum diffuser that allows the instrument to view the sun, was never designed to provide accurate calibration for more than a few years. The N7/TOMS calibration has therefore been maintained by supplementing diffuser measurements with external calibration methods[3]. These methods include Pair Justification for ozone absorbing wavelengths ($\lambda < 340$ nm) and Minimum Sea Surface Reflectivity at longer wavelengths. Since each method has its limitations, their use represents the largest source of uncertainty in long term ozone measurement using N7/TOMS.

The second TOMS instrument[4], launched onboard a Russian Meteor-3 (M3) spacecraft in 1991, has an improved calibration system which provides a means of maintaining accurate instrument calibration over a long time period. However, due to a precessing orbit, use of the calibration system is intermittent. In fact, it is during the periods when the onboard calibration system is unavailable that instrument change is the greatest. There has also been uncertainty as to whether or not the improved calibration system is working as designed.

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In the case of each TOMS instrument, an independent means of validating the instrument sensitivity characterization is desirable. Furthermore, a resolution of calibration differences between the two instruments is necessary before their measurements can be combined in a common dataset (likewise for SBUV's). The radiometric sensitivity of these instruments can, in principle, be calibrated in orbit in a way similar to their prelaunch calibration. In the laboratory, BUV instruments are calibrated using a diffuser of known Bi-directional Reflectance Distribution Function (BRDF) as a radiance source which fills the instrument field of view. A large radiance source on the surface of the earth, such as Greenland or Antarctica, can, in some ways, serve as a proxy for the laboratory diffuser. The most important feature of these land masses is that their reflective properties are relatively stable over the lifetime of a single instrument, and probably much longer. The highly reflecting ice surfaces mean that the instruments are relatively insensitive to small changes in reflectance and are least affected by the presence of aerosols in their fields of view.

3. RADIANCE MODEL

The basic method of using radiance from ice covered surfaces relies on the premise that the scene albedo (defined here as scene radiance divided by solar irradiance) remains unchanged over a period of years. Since scene albedo depends on such variables as illumination and view geometry, scene location, and atmospheric conditions, this is certainly not the case. But, by restricting the analysis, each source of scene variability can be accounted for.

The scene radiance measured by a BUV instrument can be separated into terms related to instrument change and to source change as follows

$$I_m(\lambda,t) = K(\lambda)Q(\lambda,t)I(\lambda,t) \tag{1}$$

where K is an initial calibration factor relating measured to true radiance $I(t)$, and $Q(t)$ is a quantity describing instrument throughput ($Q_{(t=0)} \equiv 1$). Changes in instrument throughput are usually a result of PMT gain change and optics degradation (exclusive of the solar diffuser). The variation of the true earth radiance can be written in terms of the underlying components: observation geometry, surface effects, and ozone[1], each of which has a its own time dependence.

$$I(\lambda,t) = I_{atm}(\lambda;\theta_o,\theta_v,\phi_o,\phi_v,\Omega,P_o,t) + I_{gnd}(\lambda;\Omega,P_o,\rho(\vec{x},\theta_o,\theta_v,\phi_o,\phi_v),t) \tag{2}$$

In this representation, the radiance is composed of atmospheric and ground components, and the incident solar flux is taken to be constant. In subsequent data analyses, scene radiance is corrected for changes in the incident solar flux. Incidence and view angles are θ_o,ϕ_o and θ_v, ϕ_v, respectively. P_o is the pressure of the lowest reflecting surface, ρ is its reflectivity, and Ω is the total column ozone amount. The effects of multiple scattering are implicitly included in the atmospheric and ground components. Scattering properties are principally affected by P_o, but they can also vary with aerosol content.

The requirement is imposed that only data from nadir views be considered in the analysis, which implies θ_v, $\phi_v = 0$. Furthermore, several simplifying assumptions are made.Azimuthal symmetry is assumed since only nadir views are considered. This is a good assumption for atmospheric scattering, but is not necessarily true for ground scenes since they are not uniformly diffuse sources. High latitude scenes, esp. over Antarctica, have the largest range of values ϕ_o in the course of a day, so analysis of data integrated over at least one day should have approximate azimuthal symmetry. Another advantage of highly reflective ground surfaces is that atmospheric scattering effects are much less dependent on the value of P_o, which in these analyses is neglected. And, dependence of the surface BRDF on geographic location, $\vec{x}$, should be small when considering a homogeneous ice sheet. The instrument fields of view naturally average over large land areas, as does integrating data collection over an extended period of time. Antarctica and Greenland earth locations are bounded as shown in Figure 1. The two remaining atmospheric variables are aerosols and ozone. In the analyses presented here, only wavelengths greater than 340 nm are considered. Since absorption by ozone at these wavelengths is not appreciable, this component can be neglected as well. Equation 2 can now be written as follows

$$\overline{I}(\lambda, t) = < I_{atm}(\lambda; \theta_o, t) + I_{gnd}(\lambda; \rho(\theta_o), t) > \tag{3}$$

where the average is explicitly over time and implicitly over ϕ_o. The presence of aerosols and clouds alters the effective BRDF of the scene[5] so that ρ becomes an explicit function of time as well as θ_o. This time dependence will, for now, be neglected. The consequence of neglecting clouds is discussed in the next section.

4. INSTRUMENT CHARACTERIZATION

Under a series of restrictions and simplifying assumptions, the earth radiance represented by Equation 3 is characterized solely in terms of the solar zenith angle θ_o. From Equation 1, the instrument throughput can be expressed relative to its initial value by

$$Q(\lambda, t) = \frac{I_m(\lambda, \theta_o, t)}{I_m(\lambda, \theta_o, t = 0)}$$

where the true radiances at times t and $t = 0$ cancel for a particular θ_o once differences in solar irradiance (sun-earth distance) are accounted for. Figure 2(a) contains a plot of Antarctic radiance as measured by M3/TOMS. Scene radiances are reported using the instrument radiance sensitivity calibrated prior to launch. The plot contains data collected over a one week period in December 1991 and is reported as the average value in 1° θ_o bins. Figure 2(b) contains a comparable plot from a week in December 1992. The ratio of the two as a function of θ_o, shown in Figure 2(c), demonstrates that the functional dependence is nearly the same in both cases, though the radiance scale is reduced in 1992. A constant ratio as a function of θ_o implies that neglecting other dependent variables, such as azimuthal angles and geographic location, is valid. The mean value of the ratio is a measure of the ratio of instrument throughput at the two times. A composite of many such mean ratios gives the relative instrument throughput as a function of time. Means are generally calculated in one week intervals, since significant instrument changes rarely occur on shorter time scales.

Deviations of the radiance ratios, seen in Figure 2(c) at high and low θ_o, represent cases where the radiance cannot be characterized solely as a function of θ_o. This often results when data being compared at the same θ_o represent vastly different earth locations or varying degrees of cloud cover. The "bad" data could be excluded from the composite instrument timeline. Rather, the results are included and reported with large uncertainties. Ratio uncertainties are determined from the spread about the mean value.

5. METEOR-3/TOMS RESULTS

A composite of radiance ratios for the Meteor-3/TOMS instrument is shown in Figure 3(a). Radiance values in the 360 nm channel are reported as values averaged over 1 week and measured relative to those of the week Dec. 18 - Dec.24, 1991. Data from both Antarctica and Greenland are used to develop the summary plot. The separate timelines from the two land masses are combined by equating the respective instrument responses during

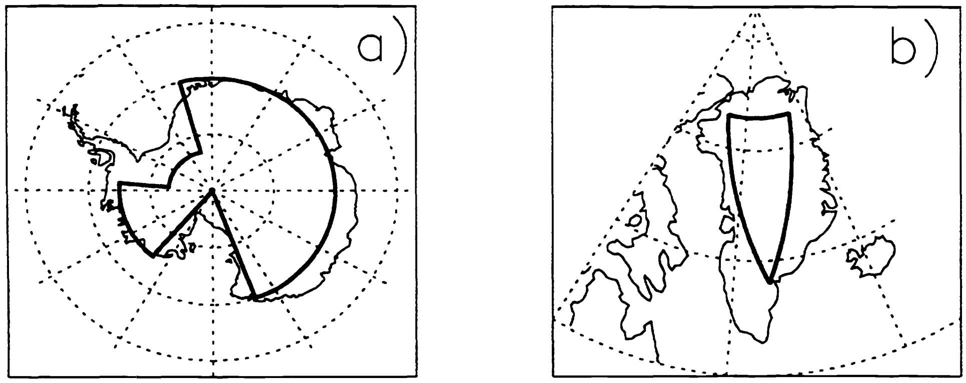

Figure 1 Geographic location of the **a)** Antarctica and **b)** Greenland sample areas. The maximum extent of the nadir view is shown.

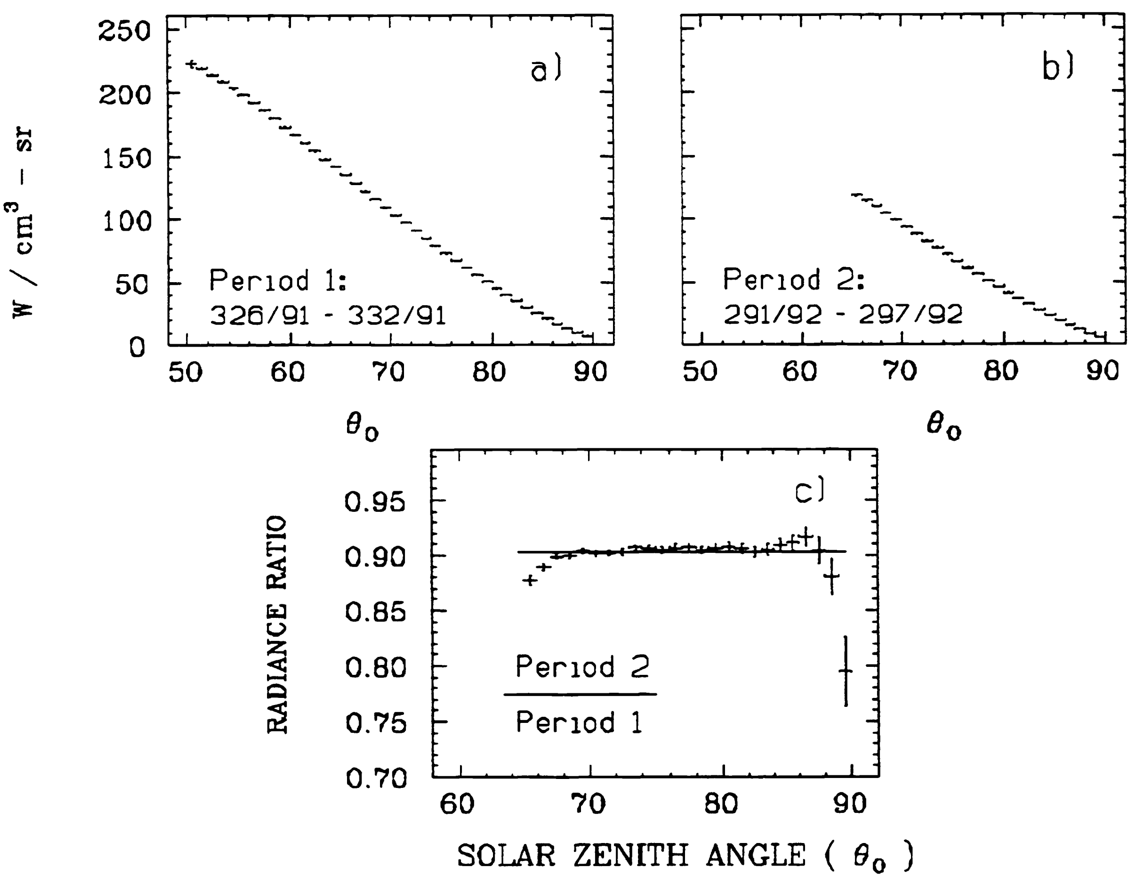

Figure 2 Average radiance measurements of Antarctica by Meteor-3/TOMS as a function of solar zenith angle (θ_o) during **a)** days 326 – 332, 1991 and **b)** days 291 – 297, 1992. Ratios of the two sets of measurements **c)** are also shown.

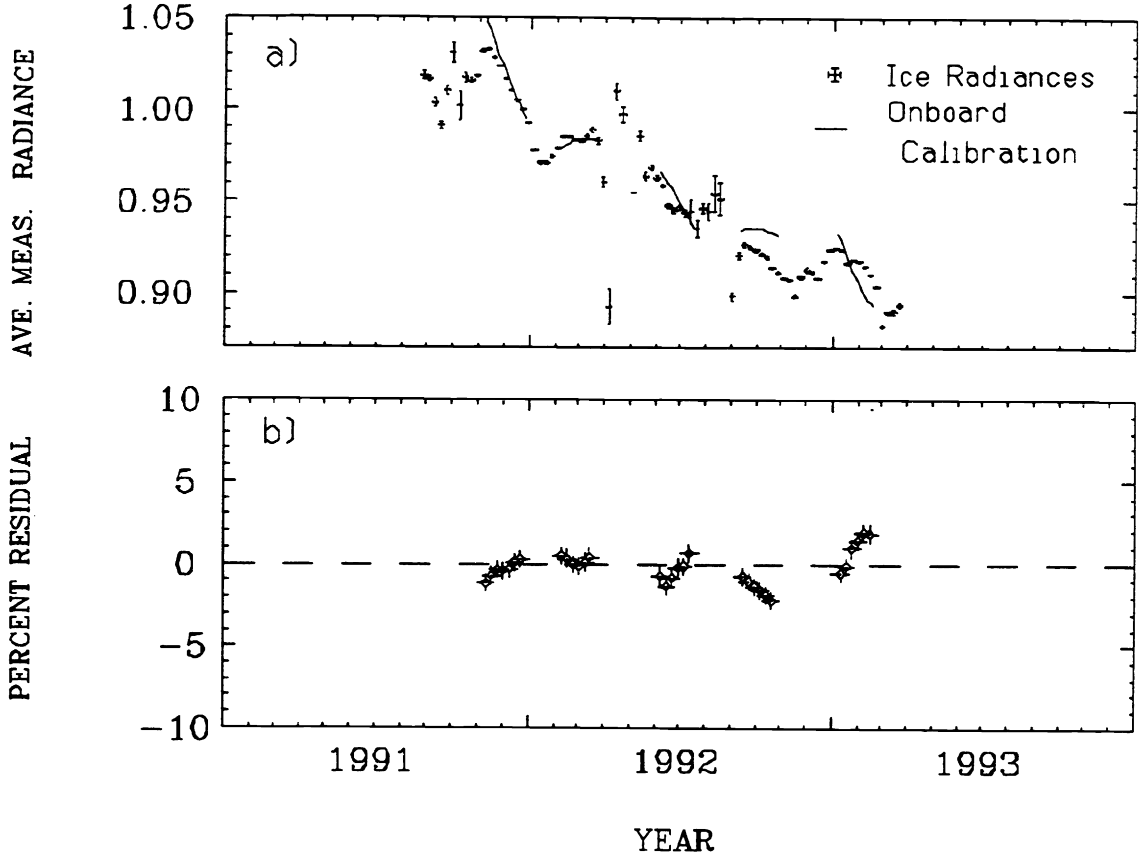

Figure 3 a) Weekly average Antarctic and Greenland radiance measured by Meteor-3/TOMS. Data are normalized to the calibrated sensitivity on day 355, 1991. Residuals **b)** relative to the calibrated sensitivity are shown as well.

times when data from both ice surfaces exist. The combined ice radiances show a marked decline in the M3/TOMS instrument sensitivity in the first 17 months since launch. The instrument sensitivity determined using the onboard calibration system, plotted in Figure 3(a) relative to the same time period in December, indicates a similar decrease. The decrease is most likely due to degradation in instrument optical throughput and/or PMT gain. While it is somewhat rapid, such a decrease is not unusual. Residual differences between a sensitivity based on radiances and onboard calibration are shown in Figure 3(b). The residuals, defined as 0 for the Dec. 1991 reference week, have at most a 2% spread which is indicative of the maximum systematic error for ice radiance measurements. Radiances appear to exhibit their largest deviations during gaps in solar observations. Such a correlation exists because instrument temperature reaches maxima during these periods and instrument response is thermally sensitive. Ice radiances have, in fact, been useful in determining instrument thermal coefficients.

6. NIMBUS-7/TOMS RESULTS

The procedure for determining N7/TOMS relative sensitivity is basically the same as that for M3/TOMS. Antarctic results are normalized to data from the week Dec. 16 – Dec. 22, 1979, while Greenland results are normalized to data from the week Jun. 17 – Jun. 23, 1984. Weekly averaged data, sampled yearly, are displayed in Figure 4(a). The Greenland and Antarctic series have each been scaled to match the N7/TOMS calibrated

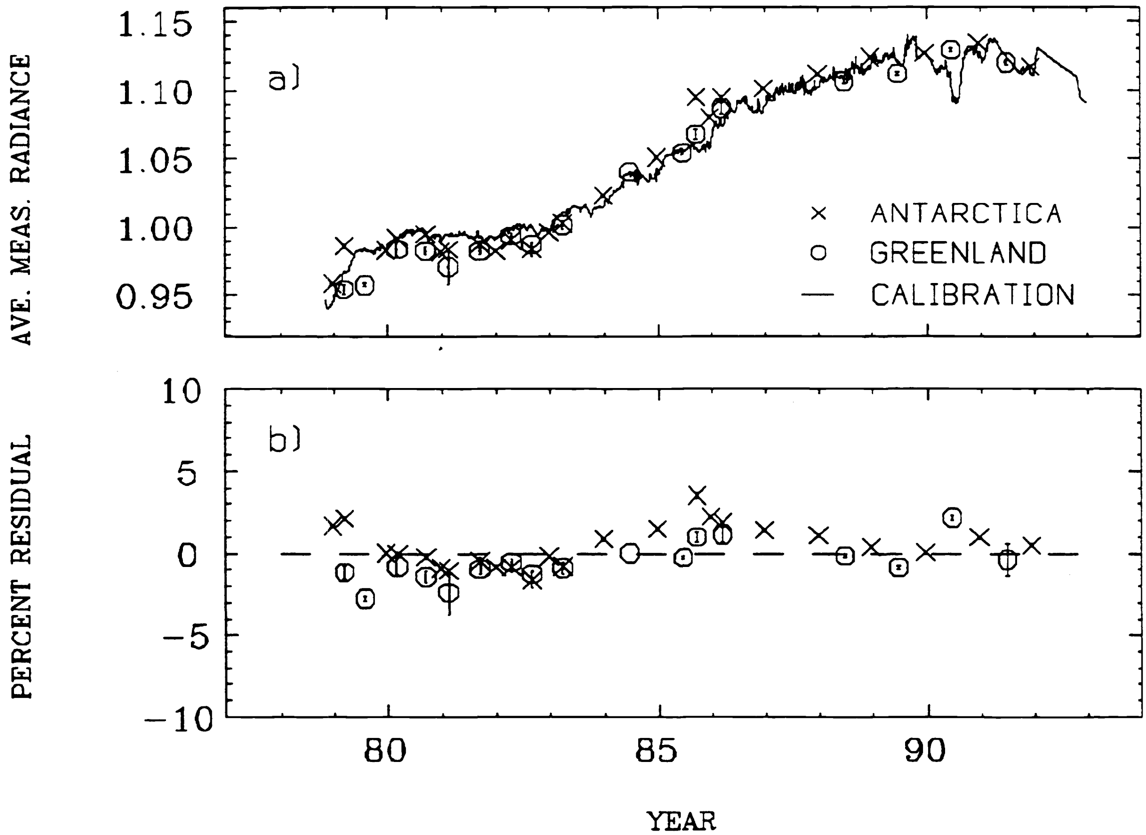

Figure 4 **a)** Weekly average Antarctic and Greenland radiance measured by Nimbus-7/TOMS. Antarctic data are normalized to the calibrated sensitivity in Dec., 1979, and Greenland data are normalized in June, 1984. Residuals **b)** relative to the calibrated sensitivity are shown as well.

sensitivity at the 1979 and 1984 time periods, respectively. This calibrated sensitivity is also shown in Figure 4. The ice radiances confirm the rather unusual result of increasing instrument sensitivity for the first 8 years after launch. Greenland and Antarctic data are in good agreement with each other as well as with the calibration data. While maximum residuals are about the same as for M3/TOMS, there are notable biases as a function of time. However, a linear regression of Antarctic residuals shows that the most recent data agree to within 1% with instrument calibration.

7. INTER-INSTRUMENT COMPARISON

The relative radiometric sensitivity between two instruments can be measured in a straightforward manner using ice radiances. Such a sensitivity ratio is useful in understanding calibration differences, which in turn is important for creating a combined ozone database. Rather than calculating a ratio of radiances at two time intervals for a single instrument, the ratio is calculated during a single time interval between the two separate instruments. The analogy of Antarctica and Greenland with a laboratory standard diffuser is particularly valid in this case. To calculate relative sensitivities, the radiance of these "diffusers" need not be known, nor need they be constant. The technique of binning in solar zenith angle is used to ensure similar viewing conditions for the two instruments. Exact spatial and temporal scene coincidences are not required because of assumptions regarding the spatial uniformity of the ice

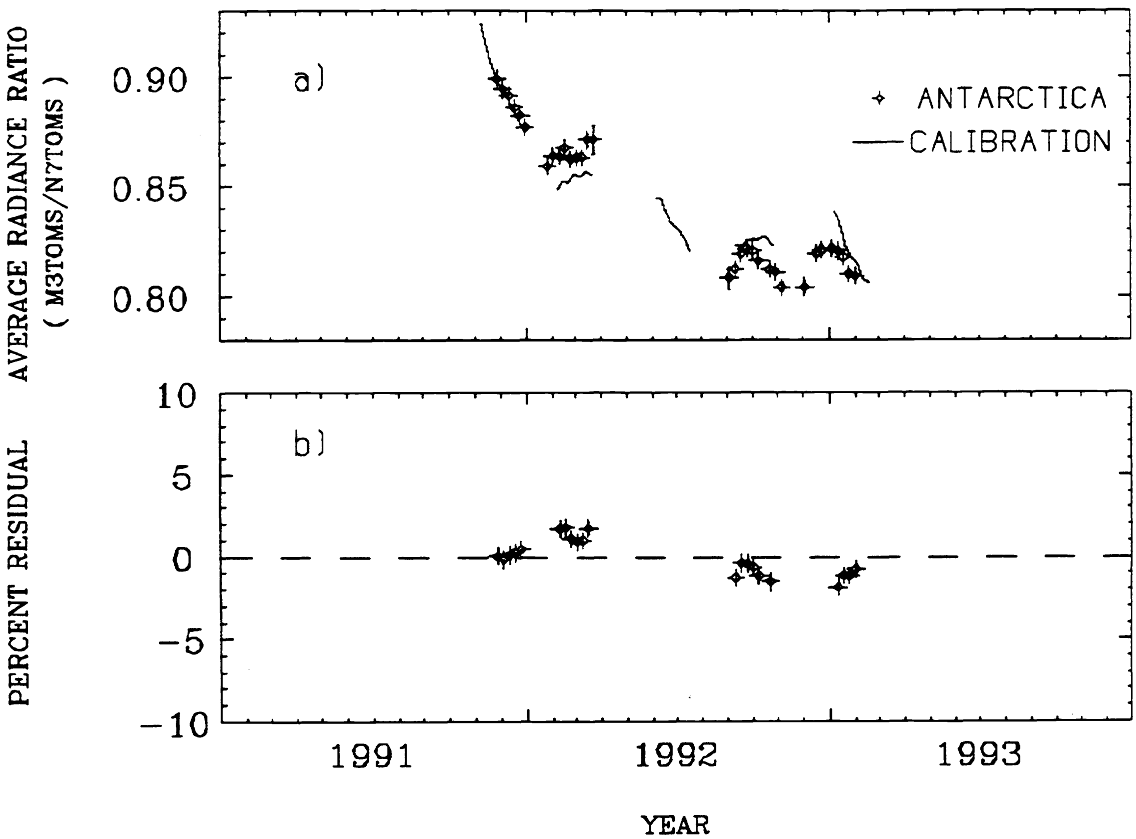

Figure 5 **a)** Weekly average Antarctic radiance measured by Meteor-3/TOMS relative to Nimbus-7/TOMS shown with the ratio of calibrated sensitivities. Residuals **b)** relative to the calibrated sensitivity ratio are shown as well.

surfaces and the one week integration period.

Figure 5(a) contains a plot of mean radiance ratios between the N7 and M3 TOMS instruments determined from Greenland and Antarctic overpasses. This plot appears similar to the M3/TOMS plot (see Figure 3) since N7/TOMS sensitivity is changing slowly relative to M3/TOMS sensitivity. The composite radiance ratio of the two instruments should equal the ratio of calibrated instrument sensitivities, shown in Figure 3 and Figure 4 as solid lines, provided the latter are normalized to 1 on the respective launch dates. The ice radiance ratios agree reasonably well with instrument calibrations. The residuals are no larger than 2%, confirming that direct inter-instrument ratios are at least as accurate as intra-instrument ratios. It is significant that the residuals are not offset from 0. This suggests the possibility that no appreciable prelaunch radiance calibration errors existed in one instrument relative to the other.

8. CONCLUSIONS

The technique described here for measuring relative BUV instrument sensitivity appears to work well at long wavelengths ($\lambda \geq 340$ nm). While several assumptions regarding atmospheric conditions and surface stability were required, the data indicate that these only marginally reduce the accuracy of sensitivity determination. The technique has been applied to the Nimbus-7 and Meteor-3 TOMS instruments with apparently good success. One measure of its success is the good agreement with instrument sensitivities determined through the standard calibration techniques. This agreement is better than 2% for both instruments. Measured ice radiances confirm the substantial decrease since launch in M3/TOMS 360 nm sensitivity and indicate that calibration techniques used for N7/TOMS are reasonably accurate.

Ice radiance ratios between M3/TOMS and N7/TOMS agree well with the ratios determined through independent calibration. The discrepancies that do exist may indicate times when one or the other instrument calibration was in error. The technique of comparing two instruments may work at ozone absorbing wavelengths ($\lambda < 340$ nm) as well, provided scene ozone amounts are similar.

9. ACKNOWLEDGEMENTS

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